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DEVELOPMENT AND EVALUATION OF A PREDICTIVE ALGORITHM FOR TELEROBOTIC TASK COMPLEXITY

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ABSTRACT

There is a wide range of complexity in the various telerobotic servicing tasks performed in subsea, space and hazardous material handling environments. Experience with telerobotic servicing has evolved into a knowledge base used to design tasks to be "telerobot friendly." This knowledge base generally resides in a small group of people. Written documentation and requirements are limited in conveying this knowledge base to serviceable equipment designers and is subject to misinterpretation. A mathematical model of task complexity based on measurable task parameters and telerobot performance characteristics would be a valuable tool to designers and operational planners. Oceaneering Space Systems and TRW have performed an independent research and development project to develop such a tool for telerobotic orbital replacement unit (ORU) exchange. This algorithm was developed to predict an ORU exchange degree of difficulty rating (based on the Cooper-Harper rating used to assess piloted operations). It is based on measurable parameters of the ORU, attachment receptacle and quantifiable telerobotic performance characteristics (eg. link length, joint ranges, positional accuracy, tool lengths, number of cameras and locations). The resulting algorithm can be used to predict task complexity as the ORU parameters, receptacle parameters and telerobotic characteristics are varied.

INTRODUCTION

The purpose of the study described here is to identify critical aspects of orbital replacement unit (ORU) changeout operations and to develop an algorithm that can predict the complexity of a teleoperated task based on the physical characteristics of the ORU, its receptacle, and quantifiable parameters of a given robot. The hypothesis was that we could develop an algorithm that predicts a task complexity rating similar to the Cooper-Harper rating used by pilots to characterize aircraft flight operations. We first developed a mathematical model of task complexity based on a combination of ORU and ORU receptacle geometries, robot kinematics, and the number, coordinates and characteristics of video cameras used for the operation. The mathematical model is expressed as the product of second order polynomial equations. The coefficients for the equations were derived by a fit to results of over 1000 different laboratory tests in which the parameters in the mathematical model were systematically varied and the resulting operator determined task complexity ratings (TCRs) recorded. The resulting algorithm is calibrated from laboratory results and can predict TCRs based on measurable parameters of the "worksite" and "work system" which accounts for the design of the ORU, its receptacle and the robot.

The resulting algorithm was tested by bringing in a new group of test subjects and comparing their TCRs to the TCRs predicted by the algorithm. These verification test results showed a significant correlation between the predicted and observed TCRs (> 95% confidence).

Once the algorithm is calibrated for a given robot system it can be used by system planners, without further testing, to:

1) Aid in improving/simplifying ORU design
2) Minimize task complexity/improve task planning
3) Identify design driving and critical verification/validation tasks
4) Optimize camera placement
5) Evaluate impacts of failed cameras, lights and manipulator joints
6) Assess improvements in robot design (link lengths, joint ranges) for a range of ORU exchange tasks
7) Aid in operator training

Alternatively, given a fixed worksite design, this methodology can be used to define the minimal/simplest robot to adequately perform the given operation. An example of this is defining requirements for a special purpose robot such as a materials processing facility robot where the worksite has been defined.

This paper presents the development approach and some evaluations of a predictive algorithm for ORU exchange. This methodology, although developed for ORU's, could be applied to a wide range of telerobotic applications beyond ORU exchange (e.g. robotic worksite set up). It's application, we believe, will significantly reduce design, test and rework time for telerobotic serviced hardware.

SCOPE AND LIMITATIONS

The development of the algorithm was based on a comprehensive set of tests limited by the hardware and laboratory set-up used (Figure 1). Four limitations were:

1. Testing and algorithm development considered only linear insertion of a box type ORU (i.e. no threading operations, j-slots, etc). Thirteen ORU configurations were used for the tests (Figure 2).

2. Testing was performed in a 1-g laboratory environment with controlled temperature, humidity and lighting.

3. Testing was performed with Oceaneering Space System's G.E. robot arm controlled by a spatially correspondent force reflecting master arm.

4. To maximize applicability of the algorithm and verification testing, parameters were normalized where possible.

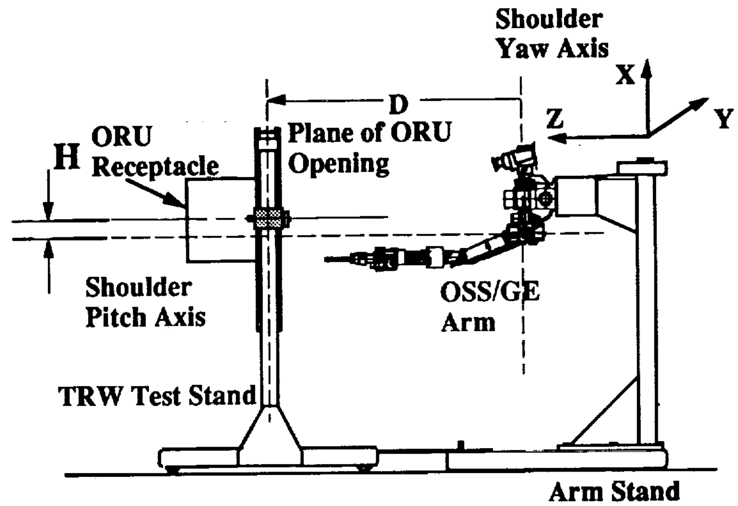

Figure 1. Test Stand and Manipulator Setup

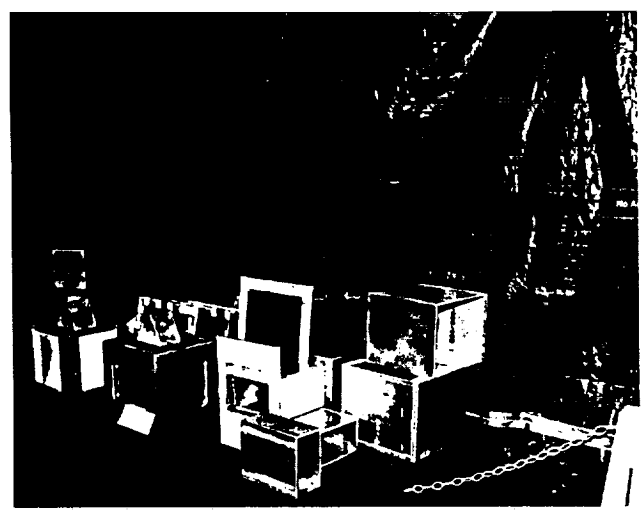

Figure 2. ORU and Receptacle Workpieces

The theoretical framework, depicted in Figure 3, suggests that the motion and information requirements of the needed task, to be successful, must intersect with the work system's (robot/tools) ability to provide motion and information.

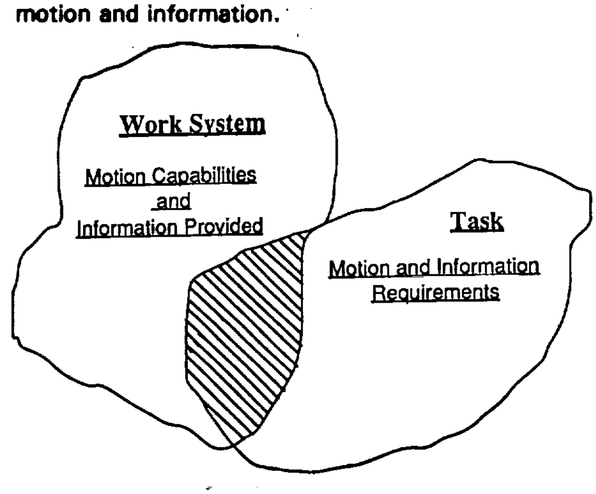

Figure 3. Theoretical Framework

TASK COMPLEXITY RATING SCALE

To describe or evaluate a task's complexity, a rating system is required. Utilizing existing research on task complexity for aircraft characteristics, the Cooper-Harper rating scale was adapted. It is assumed that task complexity of an ORU exchange can be described by the Cooper-Harper aircraft rating scale. The Cooper-Harper scale is a subjective scale used by test pilots and aircraft manufacturers to describe and evaluate the individual characteristics of a test aircraft. It is a 1-10 scale in which a 1 denotes an "excellent, highly desirable" design and a 10 denotes a design that has "major deficiencies" and requires "mandatory improvement". The rating is defined by a series of questions in the form of a decision tree. By answering each question, a pilot is driven to a rating.

To extend the Cooper-Harper rating scale to telerobotic task complexity, modifications were required in the description of the various ratings. Every attempt was made to preserve the integrity of the original decision tree, and it is assumed that the resulting TCR decision tree, (Figure 4), is consistent with the Cooper-Harper scale. The key to the success of this scale in aviation is the understanding of its use by test pilots; this understanding is the result of extensive training both as test pilots and in the use of the scale. The result of this training and familiarity is that each rating means virtually the same thing to every pilot, and that most pilots will assign the same rating to any given aircraft. The same is true for the TCR scale.

Before collecting data for calibrating the predictive algorithm a series of tests were performed to quantify the operator learning curve and develop a consistent interpretation of the TCR scale across test subjects. Test subjects were selected to be representative of SSF telerobotic operators (i.e. engineers with telerobotic operations/test experience but not full time professional

Test subjects were selected to be representative of SSF telerobotic operators (i.e. engineers with telerobotic operations/test experience but not full time professional telerobotic operators). Test subjects performed a representative series of baseline tasks 5 times with completion times recorded (Figure 5). In general, completion times leveled off after the second attempt and we concluded that the operators have an accurate gage of the TCR after the third attempt. Algorithm calibration data was, therefore, recorded after the third attempt.

Initial testing resulted in TCRs with similar trends, but wide numerical variances across the test subjects. Meetings were held to discuss individual interpretations of the TCR scale. Common definitions and interpretations resulted. We then defined a set of reference tasks across the TCR scale. The test subjects used to evaluate the derived algorithm were first "calibrated" by performing the reference tasks prior to performing algorithm calibration test runs.

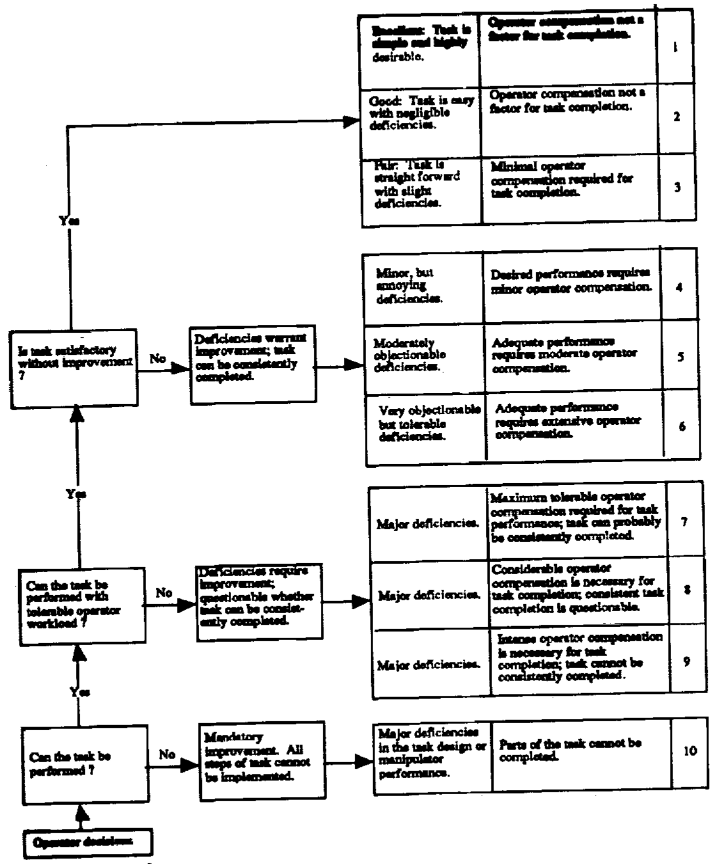

Figure 4. Task Complexity Rating Scale (Modified from the Cooper-Harper Rating Scale)

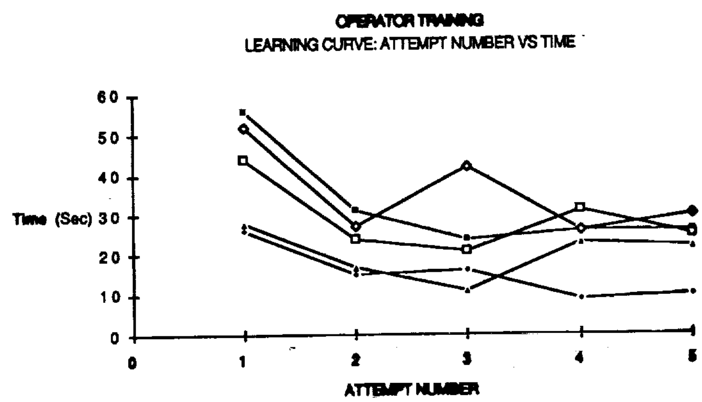

Figure 5. Operator Training Learning Curve

THEORETICAL MODEL OF TASK COMPLEXITY

Oceaneering subsea operations and robot compatible design experience suggest that task complexity is primarily a function of:

- Physical accessibility
- Visual accessibility
- Manipulation requirements
- Human/machine interfaces

These areas were divided into specific variables for individual testing and analysis. The specific variables for each area are described below:

- The physical access aspect of task complexity is influenced and defined by:
  - The gap between the ORU box and the ORU receptacle.
  - The effective interface angle between the box and the receptacle.
  - The ORU box length to gap ratio.
  - The ORU box depth to gap ratio.
  - The access region of the ORU. This is defined as the vertical or horizontal distance from the worksite insertion axis within which the manipulator wrist joint must be to insert the ORU into the receptacle.

- The visual access aspect of task complexity can be quantified by:
  - determining the task requirements in degrees of freedom (DOF) of manipulator motion
  - comparing the task DOF requirements to the manipulator, ORU, receptacle and motion information provided by the available camera views.

- The manipulation requirements can be modeled by comparing task spatial kinematics (6-DOF) to the manipulator kinematics at specific task positions and orientations. This required solving the inverse kinematic equations of motion for the manipulator.

- The man/machine interfaces include monitors and monitor placement, manipulator controls (hand controllers), and camera controls.

The relative importance of each of these areas may vary for different tasks (e.g. inserting and turning a bolt vs linear insertion of an ORU box.) A mathematical model was developed to address the first three items and each of these are discussed below. The human/machine interfaces were qualitatively accessed in an adjunctive series of tests. These interfaces tend to be independent of the ORU/robot interface and thus are not relevant to ORU designers and operational planners (the primary users of the algorithm).

The three areas described above combine to define the overall physical aspect of task complexity. In general, an insertion envelope for the ORU can be defined that must be met by the manipulator and must be visible to the cameras. The cameras must provide information to the operator that relates to the six degrees of freedom of motion available from the manipulator. The operator must control the degrees of freedom such that ORU insertion is possible. To control these degrees of freedom, specific views must be available to the operator that show the critical joint and ORU orientations and motions. The test program was defined to determine these critical views, orientations, and motions. Figure 6 illustrates the relationships described above.

Physical Accessibility - Accessibility Constraint Parameter (ACP)

The box length to gap and depth to gap ratios directly impact the amount of roll, pitch, and yaw misalignment that can be accommodated. For a given box-type ORU and receptacle, four different ratios exist. These ratios are listed below. The dimensions for the gap ratios are labeled in Figure 6. The figure also shows what is meant by the various misalignment tolerances.

Length/Gap Contribution to Roll Tolerance

- H_b/G_x (box height to gap per side in width direction)
- W_b/G_y (box width to gap per side in height direction)

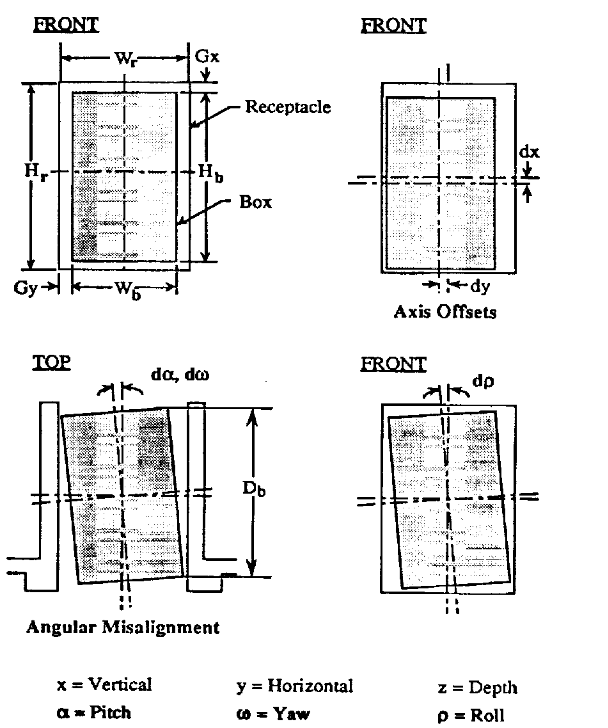

Figure 6. Illustration of Misalignment Tolerances and Gap Ratios

Where:

W_r = Width of Receptacle
W_b = Width of Box (ORU)
H_r = Height of Receptacle
H_b = Height of Box (ORU)
D_b = Depth of Box (ORU)

Depth/Gap Contribution to Pitch and Yaw Tolerance

- L_b/G_x (box depth to gap per side in width direction)
- L_b/G_y (box depth to gap per side in height direction)

For a given depth/gap ratio and given angular misalignments, the larger of the two length/gap ratios determines the amount of roll misalignment (rotational misalignment) that can be accommodated. For given length/gap ratios and a given rotational misalignment, the two depth/gap ratios determine the amount of pitch and yaw misalignment (angular misalignment) that can be accommodated. Figure 7 provides an illustration of the misalignments. The functional relationship for the misalignments are:

Capture*:

$$\theta_{pc} = f\,(H_r, H_b)$$
$$\theta_{yc} = f\,(W_r, W_b)$$

Insertion*:

$$\theta_{pi} = f\,(H_r, H_b, L_b)$$
$$\theta_{yi} = f\,(W_r, W_b, L_b)$$

* actual equations are proprietary

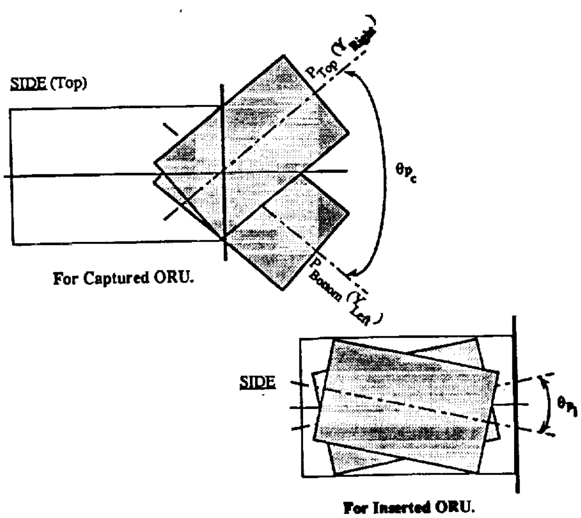

Figure 7. Physical Accessibility Angles

These angular misalignments can be used to establish a boundary into which the wrist of the manipulator must be positioned to ensure the ORU can be inserted. This boundary is referred to as the Wrist Positioned Accuracy (WPA).

Two such accuracies can be defined, which correspond to the horizontal and vertical limitations for a captured ORU. The horizontal limitation is indicated by the yaw wrist positioned accuracy and the vertical limitation is indicated by the pitch wrist positioned accuracy. An illustration of the top wrist positioned accuracy is provided in Figure 8. The functional relationship for the WPA is:

$$WPA_{pc} = f\,(L_b, \text{end-effector length}, \theta_{pc}, H_b)$$

These two wrist positioned accuracies were used to develop a third parameter, the accessibility constraint parameter (ACP). The ACP indicates the task complexity of inserting the ORU assuming that the receptacle is in an optimal position within the manipulator work space and that optimal camera views are provided. The functional relationship for the ACP is provided below:

$$ACP = f\,[(WPA_{pc}, WPA_{yc})^{-1}]$$

Where,

WPA_{pc} = pitch wrist positional accuracy for capture

WPA_{yc} = yaw wrist positional accuracy for capture

As indicated, the ACP is function of the inverses of the wrist positioned accuracies. Therefore, as the accuracies decrease the ACP and consequently, the task complexity increases.

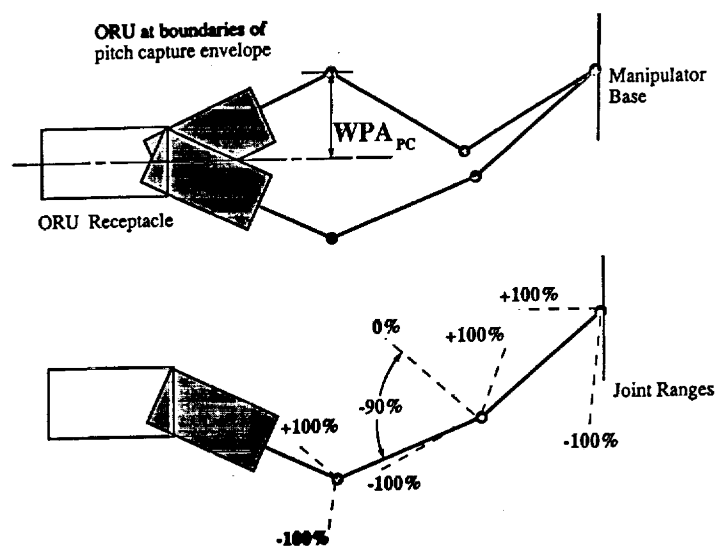

Figure 8. Pitch Wrist Positional Accuracy

Another physical parameter (that will effect the task complexity) is the lead-in geometry the ORU encounters as it enters the ORU receptacle. Given some misalignment of the ORU, the ORU will either;

- Not be captured by the lead-in
- Be captured by the lead-in but cannot be inserted because of geometric non-conformity
- Be captured by the lead-in and inserted through alignment adjustments made by the operator
- Be inserted with negligible effort from the operator because the clearance between the receptacle and ORU is such that the installation process can be completed without use of the lead-in.

The two lead-in parameters that must be considered are the effective contact angle between the ORU and the receptacle and the increase in capture area created by the lead-ins. The operator must work against the effective interface angle during a linear insertion of the ORU. The operator will have a more difficult time inserting the ORU if the interface angle is small. For small interface angles, friction forces between the ORU and the lead-in will be greater. These greater forces make sliding the ORU along the lead-ins more difficult and thus increases task complexity. However, for a given lead-in width (or thickness) a more shallow lead-in angle will also result in a larger capture area and should therefore make the task easier. This suggests that an optimal angle and lead-in width exists. As of this time, the specific impact of the lead-in angle on task complexity has not been included in the algorithm. Tests have indicated that adding a lead-in angle decreases task complexity and that steeper angles are more beneficial than shallow angles.

While the use of a lead-in profile increases the capture area of the ORU, a reduction in the manipulator resolution has the reverse effect. That is, if the manipulator cannot position an ORU within a certain positional accuracy, there will be a reduced chance of capturing the ORU within the ORU receptacle guide. The manipulator resolution is not a single value but an infinite set of values that depend on the position of the manipulator. The manipulator's sensitivity to variations in joint accuracy is a kinematic function of each joint angle, each link length, and the ordering of the joints. Therefore, in some regions of the work envelop slight changes in joint position will produce a greater variance in end-effector position in some directions than in others. The joint resolution is a critical parameter to consider for an unconstrained control mode. For a constrained motion mode, the joint resolution is much less important.

Manipulation Requirements - Kinematic Constraint Parameter (KCP)

The orientation and position of the ORU receptacle within the manipulator's work envelope are major physical constraints to the operator and were examined by studying kinematic limitations. The first kinematic limitation is performed by comparing the manipulator capability to position the wrist joint in the access envelope provided by the ORU and receptacle geometry. If limitations are imposed by the manipulator, then the WPA parameter is adjusted accordingly. The second kinematic limitation is on how much of all the joints are utilizing their joint space. Hence as joint space is used up, the ability to position the manipulator becomes more difficult. For example, an insertion task that involved moving one joint 5 degrees should be easier than a complex manipulation that utilized 100% of the available joint space.

The kinematic constraint parameter is determined by defining the coordinates of the extremes of the capture and insertion envelop relative to a reference data point (i.e. base of robot). An inverse kinematic calculation is performed to calculate the sum of the percent joint space (JS) utilized for each degree of freedom.

$$KCP = f\ (\%\ JS\ (pitch),\ \%\ JS\ (yaw))$$

Integrating Physical Accessibility and Manipulator Requirements

The combined accessibility/kinematic constrained relationship (AKCR) is expressed simply as a product of the two parameters previously defined when each is expressed as a second order polynomial.

$$AKCR = f\ (ACP,\ KCP)$$

The coefficients of the ACP and KCP second order polynomials were derived to match the TCRs from the tests to the mathematical model.

Visual Accessibility

The work system's visual equipment determines the amount of information available to the operator. The operator uses this information to determine the ORU position and orientation with respect to the receptacle as well as the orientation of the work system (robot) to the worksite (ORU receptacle). If the visual information is constrained by a lack in either quality or quantity, the task could be very complex and may be impossible to complete.

The system's visual constraints are determined by two parameters; the first parameter is the number and position of cameras, and the second parameter is the lighting condition. The number and position of cameras determines what visual information is presented to the operator. Increasing the amount of visual information was expected, initially, to decrease the task complexity. Visual information is generally increased by increasing the number of cameras focused on the worksite. However, the amount of visual information additional cameras provide may be small if they are placed in improper locations. There is also a point of diminishing returns where the operator cannot effectively process the information provided by each camera because of information overload. In the worst case, additional information can cause operator confusion.

Lighting conditions are also a visual constraint. The lighting conditions influence the value of the information received from each camera view. If the lighting conditions are poor the individual camera views may become useless. Two factors which effect the lighting conditions are the position of the lights and the light intensity. The lighting positions and the worksite configuration determine what areas of the worksite are illuminated and what areas are obscured by shadows. A camera view obscured by shadows may loose some or all of its effectiveness; this could increase the task complexity. On the other hand, shadows may help the operator estimate distances and orientations and could decrease task complexity. Testing indicated that very low light levels (30 lux) are tolerable but the time period required for ocular adjustment is extensive. Figure 9 is a time-lapsed photo taken during the test program. Hence lighting conditions are a time dependent variable and not well suited for inclusion into the algorithm. Lighting in the control room had a big impact on the ease of seeing the monitor display (i.e. no lights were the best for seeing the monitor but made it difficult to locate controls and maneuver within the workstation. Another factor on-orbit will be the relatively rapid movement/changing sun angles with time (90 min./orbit). Because of these complex issues, the lighting effects were not included in the algorithm.

The visual accessibility factors (VAFs) are determined by derived visual coefficients that define the relative importance of visual information in each degree of freedom based on ORU and receptacle geometries. Figure 10 defines coordinates for camera position relative to the worksite (ORU receptacle). Based on this coordinate system the relative importance of camera position as a function of movement of the ORU in a given plane was assessed and verified accordingly. For example, if the task has a low tolerance in pitch then the coefficient (C_v) for pitch is large. Consequently, the algorithm then gives considerable weight (importance) for a camera view that provides pitch information. Figure 11 illustrates this point. For pitch information the optimum camera placement is $\psi = 90°$, $\theta = 0°$. Other camera placements do not provide as much information on the pitch orientation of the ORU relative to the receptacle. For example, the $\psi = 0°$, $\theta = 0°$ position provides significantly less information than the optimal position provides.

Figure 9. Time-lapsed Photo of ORU Insertion in Test Fixture

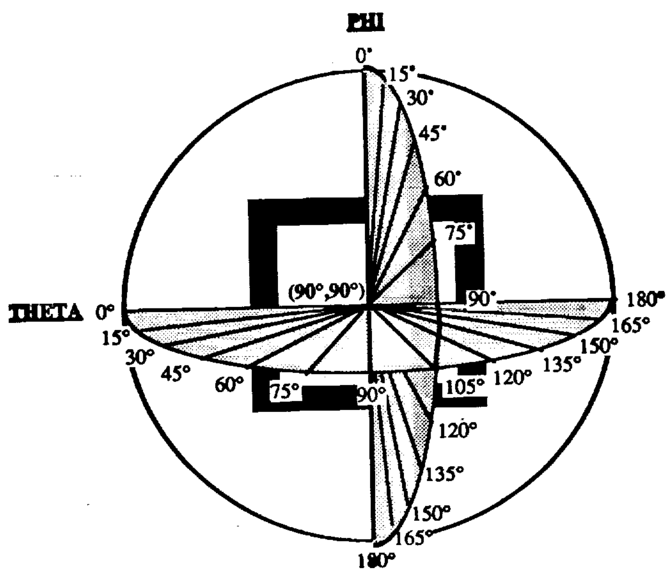

Figure 10. Camera Spherical Coordinate System

Visual diagrams, expressed in radians (e.g. Figure 12) are used to determine the visual information available from each motion direction. Surface representations in each motion direction (degree of freedom) were derived based on fundamental elements for task completion. For example, almost all of the test subjects used either edge or point information of the hardware (ORU and/or receptacle) to insert the ORU. By modeling the quality of edge and point information with respect to the camera positional angles, phi and theta, visual information was quantified. For example, a value of 1 on the surface indicates that the given camera position provides complete information about that DOF and that additional camera

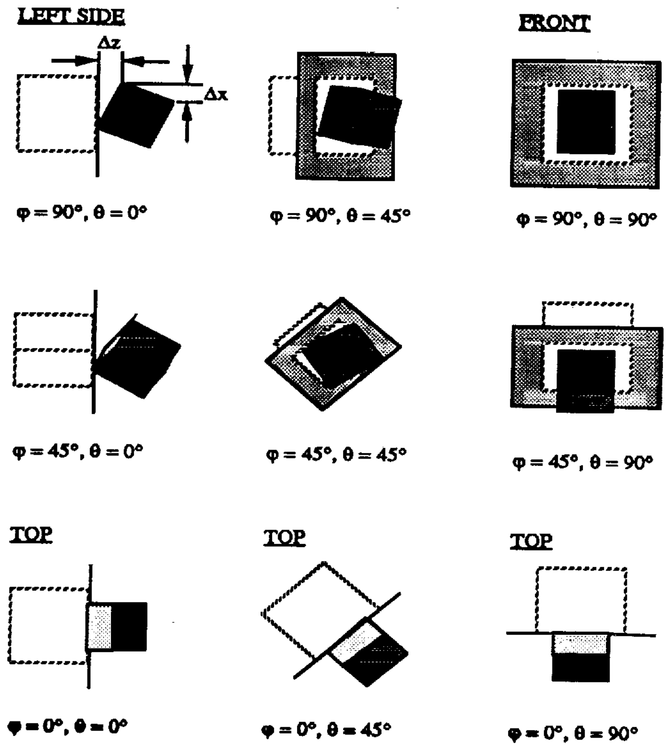

Figure 11. Pitch Visual Information as a Function of Worksite Orientation

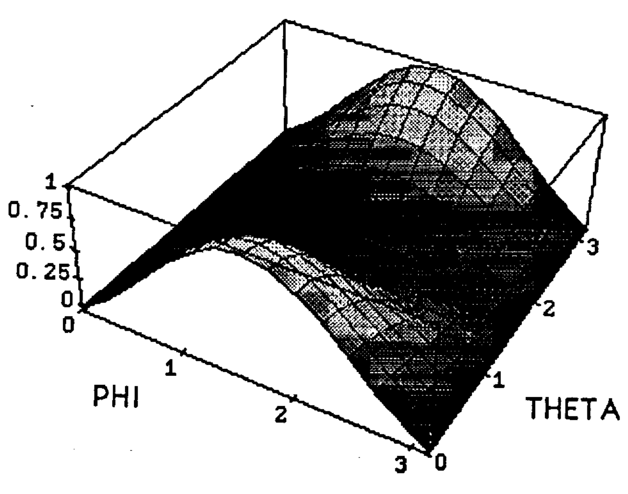

Figure 12. Surface Representation of Pitch Visual Information

views will not help. Other factors, such as the camera field of views and the video image size of vital visual information are also considered in the algorithm and modify the VAF as needed.

Final Task Complexity Algorithm

The final task complexity rating (TCR) algorithm is the product of the accessibility/kinematic constrained relationship (AKCR) and the visual accessibility factor (VAF).

$$TCR = f\,(AKCR * VAF)$$

To solve for the TCR, the algorithm iterates to determine if the task is possible, to calculate the insertion envelope, to determine if the manipulator constrains the insertion envelope and then applies visual impacts in six degrees of freedom.

ALGORITHM CALIBRATION AND VERIFICATION TESTING

Over 1000 tests were performed in the laboratory using a test fixture that allowed the worksite ORU receptacle orientation relative to the robot to be varied and 13 different ORU configurations to be used. The following parameters were varied, first separately and then in controlled groups, to determine individual and coupled effects on task complexity.

- Gaps: from 0.03" to 0.75"
- Width to Gap Ratios: from 7 to 119
- Depth to Gap Ratios: from 24 to 128
- Various Box Aspect Ratios and Sizes:
- Aspect Ratios from .57 to .83 H/W, .26 to 1.36 D/W
- Sizes from 3" to 14.75"
- Lead-In Angles: from 0° to 45°
- Work system to Worksite Variations: over 20 relative positions and orientations
- Number of Cameras: from 1 to 3 cameras
- Placement of Cameras: over 15 camera positions.

The results of these numerous tests were used to curve fit the predictive mathematical models previously developed. An interactive spreadsheet was then developed which calculates the predicted task complexity based upon user supplied worksite and work system parameters. A print out of this spreadsheet is provided in Figure 13. (in the case of Figure 13 the TCR is 6.82).

The integrated task complexity algorithm (mathematical model with coefficients fitted from test data) was evaluated by:

1) Designing a series of tests across the TCR scale on the predictions of the algorithm.

2) Comparing the predicted TCRs to the observed mean values from eight test subjects.

The verification test subjects were new, i.e. did not participate in the algorithm calibration testing. These subjects were trained on the TCR scale and reference tasks prior to performing the verification tests. The verification test results showed a significant correlation between predicted and observed TCR ($P \leq 0.05$) as illustrated in Figure 14.

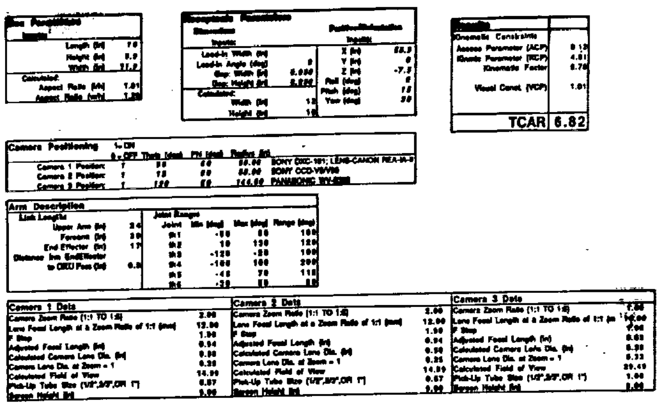

Figure 13. Interactive Input Data

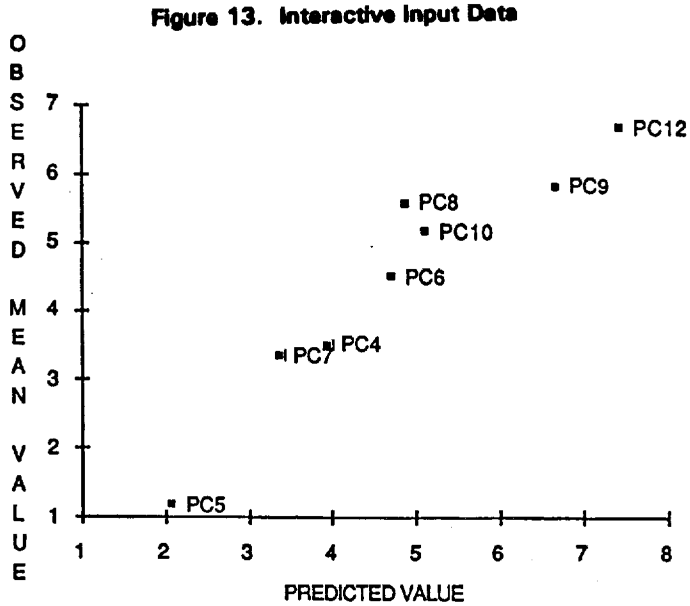

Figure 14. Verification Test Results

APPLICATIONS

We believe the TCR can be used to:

- Improve robot compatible ORU design by reducing weight and hardware complexity
- Minimize task complexity
- Identify design driving and critical verification/validation tasks
- Optimize camara placements and characteristics
- Evaluate impacts of failed cameras, and manipulator joints on complexity of specific tasks
- Optimize robot design (link lengths, joint ranges, camera placements and characteristics) based on a given range of tasks
- Aid in operator training (e.g. set up tasks that vary from low to high TCRs).

Some examples of applications are illustrated in Figure 15 - 17.

Figure 15 illustrates the insensitivity to gap width between an ORU and its receptacle. The gap for the coarse alignment could be reduced to 0.5 inches form 1.2 inches without impacting the TCR.

Figure 16 illustrates that a failed head camera for the same case as shown in Figure 15 does not impact the TCR. The other two camera views in the test were sufficient to perform the task with no more difficulty than when the head camera was operational. This type of knowledge can be very useful to an operational planner in real time when operations are underway.

Figure 17 illustrates the need to keep end effector/tool length under 22 inches to avoid impacting task complexity in this scenario.

On Space Station Freedom, the algorithm, calibrated for the Special Purpose Dexterous Manipulator (SPDM) could be used to minimize the complexity of tasks as they evolve during the operational phase and thus, minimize telerobot operations timelines. In the near-term it could help assess/verify projected task timelines.

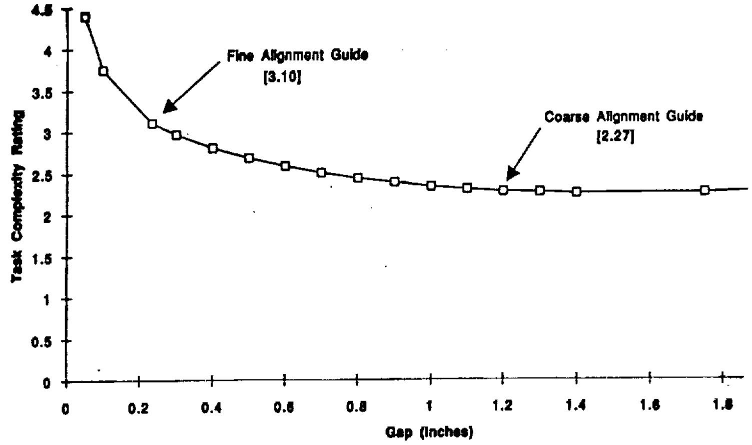

Figure 15. Gap vs Task Complexity (Nominal Camera Views)

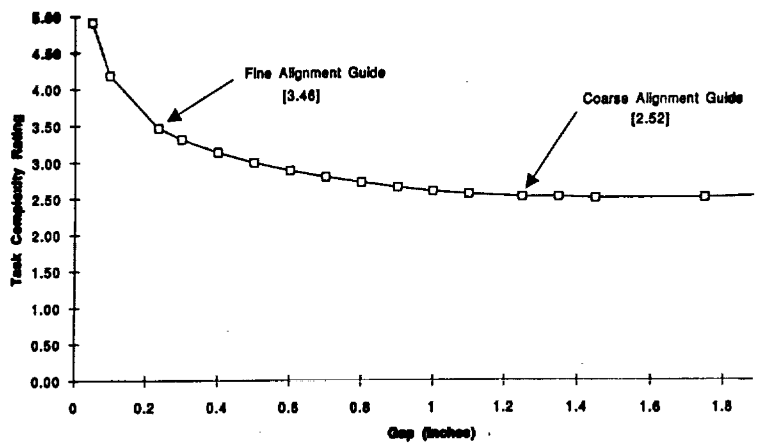

Figure 16. Gap vs. Task Complexity (Failed Head Camera)

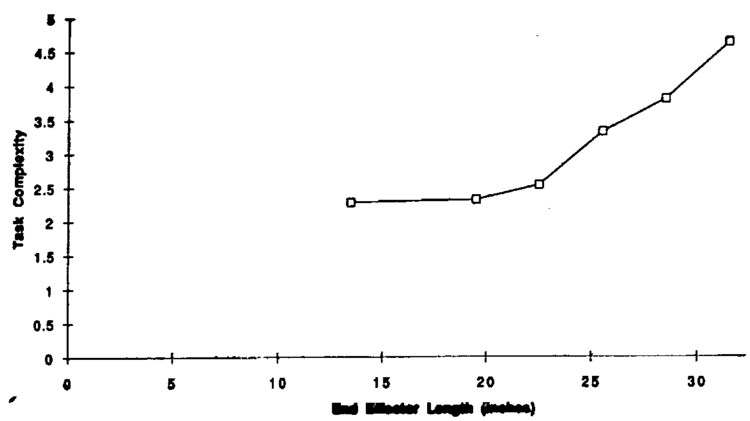

Figure 17. End Effector Length vs. Task Complexity

CONCLUSIONS

A task complexity algorithm has been developed and verified which allows serviceable hardware designers and system operators to predict telerobotic task complexity based on measurable robot and task parameters. Task or robot parameters can be varied to determine their impact on task complexity. The applications of this algorithm are far-reaching including determination of whether or not a task can be reasonably accomplished with failed system components (e.g. cameras, robot joints). As new maintenance tasks evolve on Space Station Freedom, for example, this algorithm, calibrated for the Special Purpose Dexterous Manipulator (SPDM), could be used to predict the Task Complexity and help designers/operators develop ways to minimize complexity and telerobot operations timelines.

ACKNOWLEDGEMENTS

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